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Research on Pore Structure and Fractal Characteristics of Tight Sandstone Reservoir Based on High-Pressure Mercury Injection Method

Zhengyin Li[1,2]

[1]School of Earth Science and Engineering, Xi'an Shiyou University, Xi'an, China
[2]Key Laboratory of Hydrocarbon Accumulation of Shaanxi Province, Xi'an Shiyou University, Xi'an, China
Email: 1436097234@qq.com

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Abstract

Pore structure is the key element of tight sandstone reservoir, which restricts the accumulation and flow of oil and gas in the reservoir. At present, reservoir pore structure is the focus and difficulty of unconventional oil and gas exploration and development research. The tight sandstone reservoir in the Chang 4 + 5 member of the Upper Triassic Yanchang Formation is the main reservoir for oil and gas exploration in G area. At present, there is little research on its pore structure and fractal characteristics, which to some extent affects the progress of exploration and development. This paper selects the tight core samples of the Chang 4 + 5 member in the southern edge of the Ordos Basin, and based on the high-pressure mercury intrusion experiment, uses fractal theory to study the pore structure and fractal characteristics of the reservoir in the study area, thus providing theoretical basis for the evaluation and exploration and development of the Chang 4 + 5 tight reservoir in the G area. The research results show that the lithology of the Chang 4 + 5 tight sandstone reservoir in the southern edge of the Ordos Basin is mainly feldspathic sandstone, with the highest feldspar content, followed by quartz, and the clay mineral is mainly chlorite. The reservoir has poor physical properties and strong heterogeneity. There are three main fractal characteristics in Chang 4 + 5 reservoir in G area: the fractal curve of Type I reservoir sample is in two segments, the relatively large pore has certain fractal characteristics, the pore structure is relatively regular, and the heterogeneity is weak; Relatively small pores have no fractal characteristics and pore structure is irregular. The fractal curve of Type II reservoir samples shows a three-segment pattern, and each pore size range has certain fractal characteristics, and it gradually gets better with the increase of pore size. The fractal curve of Type III reservoir samples presents a similar one-segment pattern, and the fractal dimension exceeds the upper limit of 3. It is considered that the full pore size of this type of reservoir does not have fractal characteristics, the pore throat is completely irregular or the surface is rough, and the heterogeneity is very strong.

Keywords

Tight Sand Reservoir, Reservoir Characteristics, Fractal Dimension

1. Introduction

In recent years, with the increasing demand for oil and natural gas, the difficulty of exploration and development has also increased. The global oil and gas exploration and development has shifted from conventional oil and gas to shale oil, tight oil and other unconventional oil and gas (Fu et al., 2005; Yang et al., 2013; Zou et al., 2009). The pore structure of reservoir rocks has a significant impact on the physical properties of the reservoir, the migration and storage capacity of oil and gas, and the development of the oil field. Therefore, the study of pore structure, especially the microstructure of tight reservoirs, is the focus of unconventional oil and gas development research at present (Bai et al., 2014). Pore structure is an important factor affecting reservoir fluid flow. Fractal is the general term for those shapes, structures and phenomena that have no characteristic length but have similarity. It reflects the basic attributes of a wide range of objects in nature, that is, the self-similarity of local and local, local and global in shape, function and information (Zhou et al., 1999). The pore structure of the reservoir becomes rough, tortuous and highly variable after the combination of multiple geological processes and sedimentation. Conventional models can only predict the transmission properties of the reservoir to a certain extent (He & Wu, 1999). The pore space of sedimentary reservoir has fractal characteristics, and has several structural levels of different scales. Therefore, it is feasible to use fractal theory to study the pore structure of reservoir. The tight sandstone reservoir in the Chang 4 + 5 member of the Upper Triassic Yanchang Formation is the main reservoir for oil and gas exploration in G area. At present, there is little research on its pore structure and fractal characteristics, which to some extent affects the progress of exploration and development. At present, there are many experimental methods for the study of pore structure and fractal dimension. Considering that high-pressure mercury injection has the characteristics of simplicity, high accuracy and wide detection range of pore throat, the author plans to select 10 core samples of Yanchang 4 + 5 tight sandstone reservoir in G area of Ordos Basin, and analyze its pore structure and fractal characteristics by using fractal theory through high-pressure mercury injection and X-ray diffraction experiments (Yang et al., 2015), It provides a theoretical basis for the evaluation, exploration and development of tight reservoirs.

2. Study on Micro-Pore Structure of Tight Sandstone

2.1. Experimental Principle

Mercury is a non-wetting phase for most rocks. When the pressure exerted on mercury equals or exceeds the capillary pressure of rock pore roar, the non-wetting phase mercury fluid can overcome the capillary resistance and enter the pore. The injection volume of mercury corresponds to the volume of pore throat size in porous media (Yang, 2004). According to the pore volume fraction of mercury injection and the corresponding injection pressure, the relationship curve between capillary pressure and the mercury injection saturation of rock sample can be obtained, namely the capillary pressure curve (Lu et al., 2023).

2.2. Sample Information

The experimental samples are from the Yanchang Formation 4 + 5 reservoir in the southern margin of the Ordos Basin, which is a delta front sedimentary environment. Chang 4 + 5 reservoir in the study area is a typical low porosity and low permeability reservoir, with a porosity of 3.0% - 10.7% and an average of 8.1%; The permeability is 0.04×10^{-3} - 1.28×10^{-3} μm^2, mean 0.29×10^{-3} μm^2. The rock type is mainly feldspathic sandstone. The results of X-ray diffraction show that the content of feldspar is the highest, the mass fraction is 48.0% - 60.4%, and the average is 55.9%; The content of quartz takes the second place, the mass fraction is 18.3% - 34.0%, and the average value is 55.9%; The mass fraction of clay minerals is 5.6% - 26.0%, with an average of 13.5%. The clay minerals are mainly chlorite, followed by illite and kaolinite, and a small amount of illite-mongolian mixed layer can also be seen.

2.3. Mercury Intrusion Curve Characteristics

The typical mercury injection curve can generally be divided into three sections: rising section, stable section and upwarping section. The curve shape reflects the development of pore throat and connectivity of the reservoir. The 10 samples can be divided into three types according to the mercury intrusion curve.

Type I samples include G4-1, G4-5, G5-5 and G4-19. The porosity of Type I samples is between 8.5% and 10.7%, and the average porosity is 9.3%; Permeability between 0.14×10^{-3} - 0.66×10^{-3} μm^2, the average value is 0.36×10^{-3} μm^2; The middle flat section of the capillary pressure curve is long and deviates to the upper right (**Figure 1**). The average displacement pressure is 0.94 MPa. There are many large pores and throats (average skewness coefficient 1.739). The separation is good (average separation coefficient 0.232), and the final mercury saturation is high. Type I sample is the reservoir with the best reservoir capacity and percolation capacity in this area.

Type II samples include G4-7, G4-9, G4-11 and G4-15. The porosity of Type II samples is between 8.6% and 10.0%, and the average porosity is 9.1%; Permeability between 0.19×10^{-3} - 1.28×10^{-3} μm^2, the average value is 0.53×10^{-3} μm^2; The middle flat section of the capillary pressure curve is lower left relative

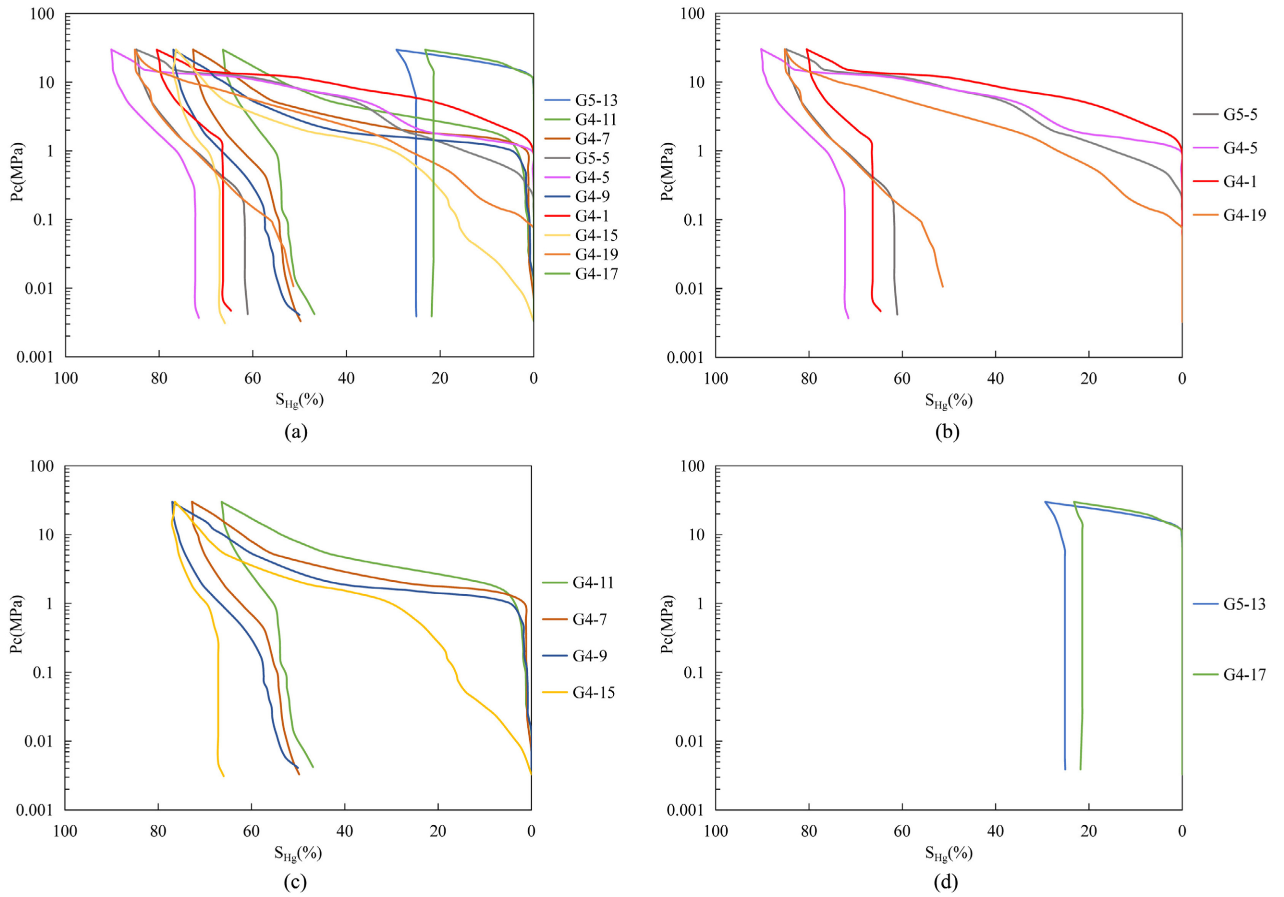


Figure 1. Capillary pressure curve of reservoir in G area. (a) All samples; (b) Type I samples; (c) Type II samples; (d) Type III samples.

to the Type I sample (**Figure 1**), the average displacement pressure is 0.85 MPa, there are many large pore throats (average skewness coefficient 0.838), the sorting property is medium (average sorting coefficient 0.182), and the final mercury saturation is medium. Type II sample is a reservoir with coexistence of macropores and micropores, which is the reservoir with the second best reservoir capacity and percolation capacity in this area.

Type III samples include G5-13 and G4-17 samples. The porosity of G5-13 sample is 8.6%; The permeability is 0.06×10^{-3} μm^2; The flat section in the middle of the capillary pressure curve is short and inclines to the upper right (**Figure 1**). The displacement pressure is the largest (12.031 MPa), the skewness coefficient is 0.769, the separation coefficient is 0.009, and the final mercury saturation is low. The pore throat of Type III sample is small, and the reservoir capacity and seepage capacity are poor.

3. Study on Fractal Characteristics of Tight Sandstone Reservoir

3.1. Principle of Fractal Theory

The French mathematician Mandelbrot et al. first proposed the fractal theory in

1975, which was used to describe the structural characteristics of complex objects in nature. At present, it is widely used in the fields of reservoir fracture prediction, pore structure and heterogeneity. The most important thing about fractal is self-similarity. A self-similar object is considered to have similar structural characteristics at different scales. Objects with fractal characteristics can be represented by fractal dimension *D*. Generally, the fractal dimension of porous rock is 2 - 3. The closer the fractal dimension is to 2, the weaker the reservoir heterogeneity is. The closer the fractal dimension is to 3, the stronger the heterogeneity is, the more complex the reservoir pore structure is. Fractal dimension can better reflect the heterogeneity characteristics of complex pore structure (Lu et al., 2023).

3.2. Fractal Dimension Calculation

According to the mercury intrusion capillary model and fractal theory, the Formula (1) can be obtained (Chen et al., 2022):

$$N(r) = \frac{V_{\mathrm{Hg}}}{\pi r^2 L} \propto r^{-D_f} \tag{1}$$

where: $N(r)$ is the number of pores with a radius of r; R is the pore radius (μm); L is the capillary length; V_{Hg} is the volume of mercury; D_f is the fractal dimension.

According to the Y-Laplace equation, the capillary pressure P_c is converted into the pore throat radius, and the calculation formula is:

$$P_c = \frac{2\sigma\cos\theta}{r} \tag{2}$$

where: P_c is the capillary force, MPa; σ is the surface tension, N/m; θ is the contact angle, (°).

By bringing Equation (2) into Equation (1), the relationship between the mercury inlet volume V_{Hg} and the capillary pressure can be obtained as:

$$V_{\mathrm{Hg}} \propto P_c^{-(2-D_f)} \tag{3}$$

The relationship between mercury saturation S_{Hg} and mercury volume V_{Hg} can be expressed as

$$S_{\mathrm{Hg}} = \frac{V_{\mathrm{Hg}}}{V_p} \tag{4}$$

In Formula (4): V_p is the sample pore volume, %.

Substitute Formula (4) into Formula (3), and the relationship between mercury saturation and fractal dimension D_f is

$$S_{\mathrm{Hg}} = aP_c^{-(2-D_f)} \tag{5}$$

In Formula (5): "a" is a constant.

Take the logarithm of both ends of Equation (5) to get the $\lg P_c - \lg S_{\mathrm{Hg}}$ fractal curve, and get the fractal dimension $D_f = H + 2$, where H is the slope of the fractal curve. The upper limit of fractal dimension 3 corresponds to a completely irregular or rough surface, and the lower limit 2 corresponds to a completely smooth surface (Chen et al., 2022).

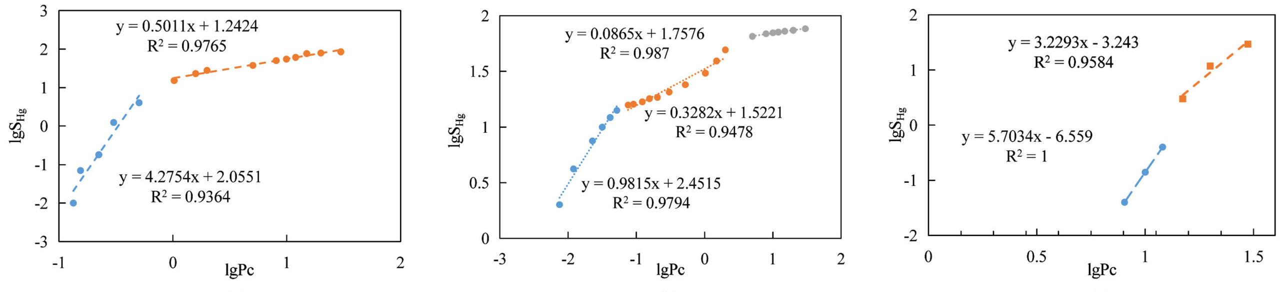
3.3. Fractal Dimension Calculation Results

High-pressure mercury injection test is widely used to evaluate reservoir porosity, with the advantages of wide range of pore size and low cost (Lyu et al., 2022). According to the above method, the 10 groups of data measured in the mercury intrusion test are plotted as scatter plots in the $\lg P_c - \lg S_{Hg}$ coordinate system, and the fractal dimension is calculated. The fitting results are shown in **Figure 2**.

From the fractal characteristic curves of various samples (**Figure 2**), it can be seen that the relationship curve between lg$S$ and lg$r$ is not a straight line, but a number of straight lines with inflection point. It is believed that the pores of the tight sandstone of the Chang 4 + 5 member in the southern edge of the Ordos Basin G area have multifractal characteristics, and the pores of different reservoirs in the formation have different fractal characteristics. The radius of the pore throat corresponding to the turning point is the boundary. The pore throat of the sample is divided into relatively small holes, medium holes and relatively large holes. The fractal dimension of each pore of the sample is calculated by the slope of the fitting curve. The fractal dimensions of the relatively small holes, medium holes and relatively large holes are recorded as D_1, D_2 and D_3 respectively.

It can be seen from the fractal curve characteristics that the fractal curve of G5-5 sample is in two segments, and the fractal curve D_3 of the relative macropore is 2.50, indicating that the sample has a certain fractal characteristics of the relative macropore, and the pore structure is relatively regular, with a certain degree of heterogeneity; The fractal dimension of the relatively small pore below the turning point is greater than 3, indicating that the corresponding relatively large pore does not have fractal characteristics and the pore structure is irregular.

The fractal curve of G4-15 sample is three-segment, and the fractal curve D_3 of the relative macropore is 2.09, indicating that the relative macropore of the



(a) (b) (c)

Figure 2. Fractal characteristics of reservoir pores of different types of samples. (a) Type I sample (G5-5); (b) Type II sample (G4-15); (c) Type III sample (G5-13).

sample has excellent fractal characteristics, regular pore structure and strong homogeneity; The fractal curve D_2 of the mesopore is 2.32, which indicates that the mesopore in the sample has certain fractal characteristics, the pore structure is relatively regular, and has certain heterogeneity; The fractal curve D_1 of the relative pore is 2.98, which is close to the upper limit of fractal dimension 3. The relative pore of the sample does not have fractal characteristics, and corresponds to a completely irregular or rough surface, with strong heterogeneity.

The fractal curve of G5-13 sample presents a two-part formula with nearly the same slope (R^2 is more than 0.9 according to the one-stage formula), and the fractal dimension of the two sections is far greater than the upper limit of fractal dimension 3. It is considered that the sample has no fractal characteristics in the full aperture, the pore throat is completely irregular or the surface is rough, and the heterogeneity is very strong.

4. Conclusion

1) The lithology of Chang 4 + 5 reservoir in G area on the southern edge of Ordos basin is mainly feldspathic sandstone, the rock composition is mainly feldspar, and the clay mineral is mainly chlorite. The physical property of the reservoir is poor, the average porosity is 8.1%, and the average permeability is 0.29×10^{-3} μm^2 is a typical low porosity and low permeability tight reservoir.

2) Based on the high-pressure mercury injection test, the Chang 4 + 5 reservoir in G area is divided into three types. Among them, Type I reservoir has good physical properties and good connectivity between pore and throat, which is the reservoir with the best reservoir capacity and seepage capacity in this area. Type I reservoir has certain fractal characteristics with relatively large pores, regular pore structure and weak heterogeneity; The relatively small pores have no fractal characteristics and the pore structure is irregular; The pore size range of Type II reservoir has certain fractal characteristics, and gradually gets better with the increase of pore size; The full pore size of Type III reservoir does not have fractal characteristics, the pore throat is completely irregular or the surface is rough, and the heterogeneity is very strong.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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